Rheological properties of low consistency TMP from thinning wood of Chinese Fir

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Abstract: The rheological behavior of low consistency thermomechanical pulp of Chinese fir harvested by intermediate thinning was analyzed. The results show that the apparent viscosity of pulp changed along with the beating degree, pulp consistency and shearing velocity. With the increasing of pulp consistency, the apparent viscosity of pulp increased gradually. Beating degree of pulp had an effect on microstructure of pulp. The apparent viscosity of pulp declined as beating degree of pulp increased, and the apparent viscosity of pulp fell along with the shearing velocity increasing. Based on the results, the rheological models are set up. The models showed that the fluid types of the low consistency pulp could be described as pseudoplastics fluids (non-Newtonian fluids).

Keywords: Thermomechanical pulp; Chinese Fir; Thinning wood; Low consistency pulp; Rheological properties; Pseudoplastics fluid

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Introduction

Pulp molding products were formed by pressing plant fiber mixed with some water and oil proofing additives. Due to its degradable properties under natural conditions, at present pulp molding products have been one of the ideal packaging materials to replace epispastic polystyrene (EPS) whose discards result in the so-called notorious whiteness contamination. On the other hand, Chinese fir (*Cunninghamia Lanceolata*) has been the dominated species of artificial plantations in South China. How to utilize the timbers harvested by thinning has also been one of the urgent affairs for the plantation forests management. Pulping by alkaline chemical technology is one of the major approaches to utilizing thinning timbers of Chinese fir plantation. However, because of its low fiber yield, contamination caused by chemical additives and high-energy consumption, chemical pulping of Chinese fir used in molding products industry encountered embarrassment. Compared with chemical pulping technology, the thermo-mechanical pulping has such advantages as higher fiber yield, lower contamination, lower energy consumption, and lower preparation cost. Furthermore, the thermomechanical pulp (TMP) from Chinese fir thinning wood contains much lignin. Its fiber is soft and of lower bulk density compared with other needle-leaved wood pulps such as that from Masson's pine (*Pinus massioniana*) in South China. Therefore, TMP is suitable raw material for molding products. For the reasons mentioned above, we developed the ZMC-1.5Q pulp molding products line adopting the TMP from thinning timbers of Chinese fir plantation to provide an effective approach for the utilization of the thinning timbers of Chinese fir plantation and an available solution to dealing with whiteness contamination (Miao *et al*. 1998; Qiu *et al*. 2000; Wang *et al*. 2000).

Rheological properties of pulp are major physical properties of pulp that play crucial roles in design of pipe transferring system of pulp molding product line, because they have most dramatic influence on flow characteristics of a fluid. For example, the apparent viscosity of pulp is one of the major parameters to calculate the friction of pipe and determine the transferring equipments and technology. In addition, it is also an index of pulp quality during the processing of pulp molding products. The pulp is a special fluid. The rheological properties will be complicated with pulp's composition and surrounding conditions. The solid concentration, consistency, microstructure of fiber and shearing rates deemed to influence the rheological properties of pulp (Chen 1992; Fu *et al*. 1999; Zaman 1995, 1996). There have been many intensive studies of rheology on such fields as food industry and agricultural materials (Velez and Barbosa 1998; Cha *et al.* 1999; Carson and Sun 2000; Michele *et al*. 2001; Togrul and Arslan 2004; Landry *et al*. 2004). However, little attention was paid to the rheological properties of low consistency TMP, especially for those suitable to be the raw materials for pulp molding products. Thus, this study investigated the rheological properties of TMP from Chinese fir thinning wood with different consistencies, beating degrees and shearing rates, and intended to provide the basis for the design of transferring system of pulp molding product line.

Materials and methods

Materials

The TMP from Chinese fir thinning wood was provided by Jiangle Pulp and Paper Company in Fujian Province. Pulp brightness is of 60% (ISO). Pulp's physical and chemical properties of TMP are described as follows: Average length 2.26 mm, Average width 39.65μm, Average thickness of cellular wall 4.8 μm, Length-to-width ratio 66.1, Cellulose 46.65%, Pentosan 8.60%, Klason lignin 31.96%.

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Test methods

Constant-weight dry TMP board was selected and was torn into pieces of size of 4 cm× 4 cm approximately. Then the pieces were dipped in distilled water and being kept for 4 hours. Following, the TMP was beaten by Valley Beating Machine (Model of ZQS_2-23L, manufactured by the Machines Factory of Northwest Light Industrial Institute) with four beating degree levels of 15°SR, 20°SR, 25°SR, 30°SR. Then different consistencies TMP for testing rheological properties were prepared for rheological properties test. The shearing velocities were manipulated at four different levels showing in spindle's speed of 6, 12, 30 and 60 rpm.

The beating degree of TMP was determined by Schopper-Riegler method under the China National Standard GB/T3332-1982. The apparent viscosity of TMP was measured by NDJ-9S Data-presentation Rheometer (Shanghai Scaling Apparatus Factory).

Results and discussion

Effects of consistency of pulp on apparent viscosity

Generally, the consistency of TMP used in pulp molding products ranges from 0.6% to 6.0% (Chen 1996). The pulp ranging from such consistency has been viewed as low consistency pulp, which has rather good fluidity (Chen 1996). The solid fiber content of pulp has a great effect on rheologial properties of TMP from Chinese fir thinning wood. As shown in Fig. 1–Fig. 4, the apparent viscosities increase along with pulp consistencies, which may result from internal friction increase of pulp. The fibers in pulp are easily combined with water, but they cannot dissolve in water. The apparent viscosity is caused by the cohesion between fibers and water molecules, which may prevent pulp from flowing and deforming. Also, fibers in pulp can be congregated and wrapped together, which may result in the internal friction increase of pulp, and lead to apparent viscosity rising synchronously. With pulp consistency decreasing, the water molecules may decentralize the wrapped fibers to some extent and induce the apparent viscosity declining. On the other hand, due to the fiber's characteristics of easily combining with water molecules, the interactions taken place between fibers and water molecules are very complicated. Therefore the apparent viscosity increment is not linearly correlative to the pulp consistency. When the pulp consistency reaches a specific point, the elasticity collision might occur among fiber particles, which also results in rising of apparent viscosity.

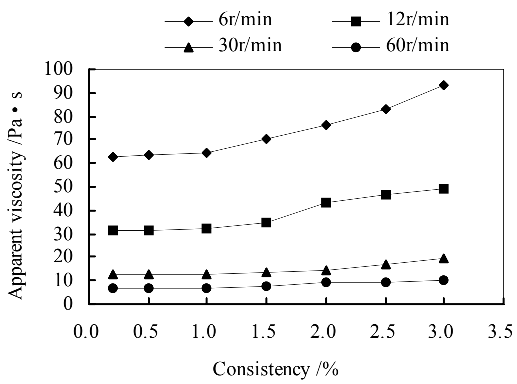

Fig. 1 The apparent viscosities of different pulp consistencies （15°SR pulp beating degree）

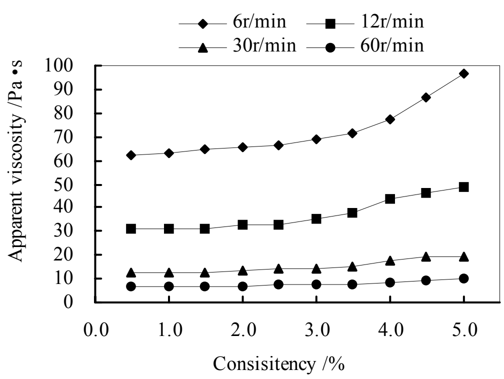

Fig. 2 The apparent viscosities of different pulp consistencies（20°SR pulp beating degree）

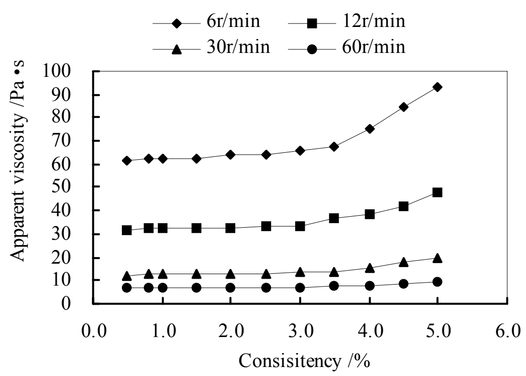

Fig. 3 The apparent viscosities of different pulp consistencies（25°SR pulp beating degree）

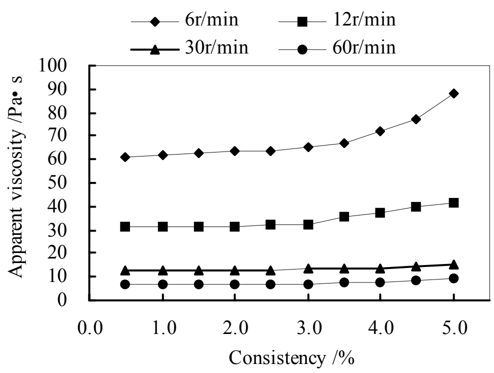

Fig. 4 The apparent viscosities of different pulp consistencies（30°SR pulp beating degree）

Effects of beating degrees of pulp on apparent viscosity

A single fiber in pulp can be viewed as a solid particle (Fu 1998). The beating degree has an effect on microstructure of fiber (Fu *et al*. 1999; Chai *et al*. 2000; Li *et al*. 2001). For the pulp of high beating degrees, its fiber particles are relatively small. The interaction strength between fiber particles and water molecules is rather weak. This may lead to the apparent viscosity

falling down. For low consistency pulp, fibers can interlace together and form link-up networks. The networks strength is correlated to fiber rigidity and the fiber length-to-width ratio (Fu *et al.*1999). The fibers of pulp with high beating degrees are short and forcible, while the fibers of low beating degree pulp being soft and long. Therefore, the fiber networks of different strength were formed. The shearing force to decentralize the networks is also very different, which may illustrate the results of viscosities of different beating degrees shown in Fig. 5–Fig. 8.

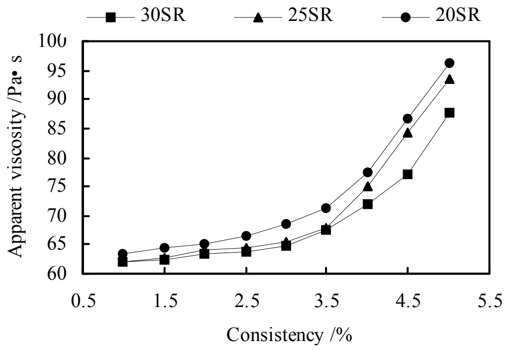

Fig.5 The apparent viscosities of different beating degrees (6r/min rotation speed)

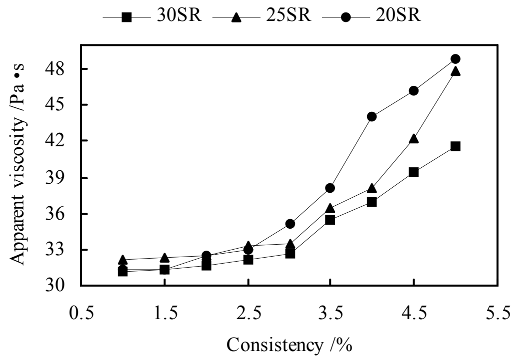

Fig.6 The apparent viscosities of different beating degrees (12r/min rotation speed)

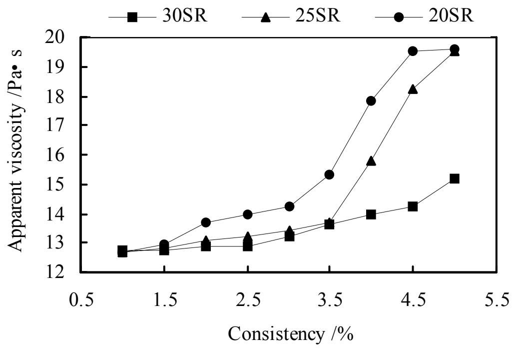

Fig.7 The apparent viscosities of different beating degrees (30r/min rotation speed)

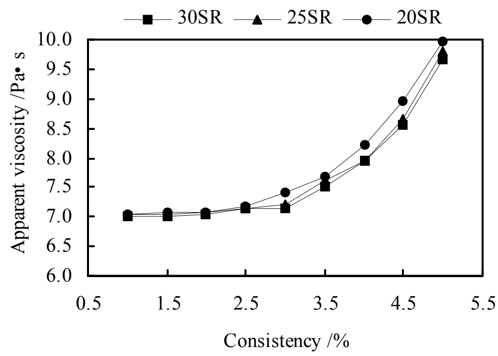

Fig.8 The apparent viscosities of different beating degrees (60r/min rotation speed)

The shear velocity may change apparent viscosity. As shown in Fig. 9–Fig. 12, with the increasing of shearing rates expressing in spindle's speed, the apparent viscosities declined significantly. In particular, it is evident that the apparent viscosity decreased for the high pulp consistencies. Because the consistency of pulp used in molding product is greater than the critical consistency which is of 0.05% to 0.1% generally, opportunities are provided for fibers to collide each other. When the shearing stress to which the fibers being subjected is not too great, it is possible for fibers to form interlaced and link-up networks. It needs a certain shear force to decentralize those fiber networks. On the other hand, when measuring the apparent viscosity of pulp, the spindle was circumrotating under a rather low speed condition. There is a free boundary interface between the surface of fiber networks and the outer surface of spindle. The free boundary interface exists between surface of fiber networks and the inner surface of canister of rheometer as well. The free boundary interface consists of tiny fiber particles mixed with water molecules, which is so-called water circumfluence. The water circumfluence contains few fibers and can be looked as a layer of water membrane. With the spindle speeding, water circumfluence begins to rush over and draw fiber particles from the surface of fiber networks, which leads the networks to disintegrate and exhibits the apparent viscosity of pulp falling down.

Besides the fiber networks in pulp, there are also some assembly fiber bundles which are formed by some much tightly interlaced and wrapped fibers. The single fiber of the network or assembly bundles is subjected to the pulling stress of other fibers, i.e., the inner stress of fiber. Because every fiber can endure a certain pulling stress and there is friction or combination strength among the surface of fibers, it needs a certain shearing strength to separate the interlacing fibers. The greater the spindle speed, the greater the shearing strength is. The shearing force may pull the fibers within networks straightly to some extent and reduce the wrapping points of fibers. Therefore, the apparent viscosity of pulp falls along as the shearing velocity increases as shown in Fig. 9–Fig. 12.

Regression analysis of rheological properties parameters of low consistency TMP from Chinese fir thinning wood

The rheological properties of low consistency pulp can be described by such parameters as η_a , K and n, where η_a (Pa·s) is apparent viscosity, K(Pa·s ^{n}) is consistency coefficient and n (no dimension) is the index of fluid characteristics. For Newtonian

fluid, the relationship between shearing velocity and rotation velocity of outer surface of rheometer's spindle can be described by following equation (Han *et al*. 1993):

$$y_N = \frac{2\Omega R_2^{\ 2}}{(R_2^{\ 2} - R_1^{\ 2})} \tag{1}$$

Where γ_N, is the shear velocity of outer surface of rotor, s^{-1}, Ω the rotation velocity of inner canister of rheometer, $rad{\cdot}s^{-1}$, R_2 the radium of outer canister of rheometer, m, and R_1 the radium of inner canister of rheometer, m.

Assume N to be the spindle velocity per minute, rpm, then the following equation can be deduced:

$$y_N = 0.2094\frac{R_2^{\ 2}}{R_2^{\ 2} - R_1^{\ 2}} \cdot N = K_1 N \tag{2}$$

Where, γ_N, R_2, R_1 are the same as that of above. K_1 (no dimension) is a constant determined by survey system and can be calculated as below:

$$K_1 = 0.20944\frac{R_2^{\ 2}}{R_2^{\ 2} - R_1^{\ 2}} \tag{3}$$

Where, R_2 and R_1 are the same as that of Equation (1).

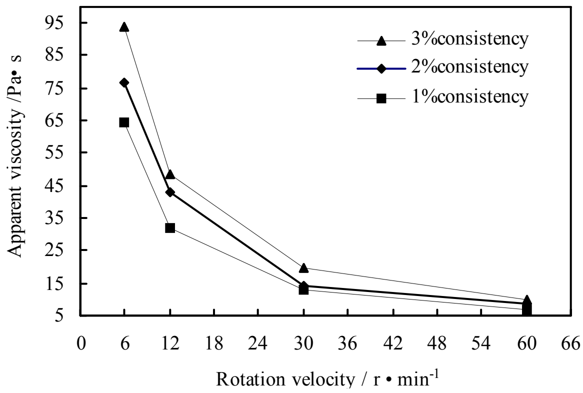

Fig.9 The apparent viscosities of different rotation speed (15°SR beating degree)

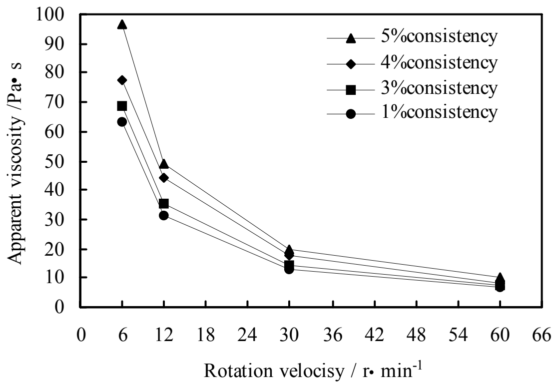

Fig.10 The apparent viscosities of different rotation speed (20°SR beating degree)

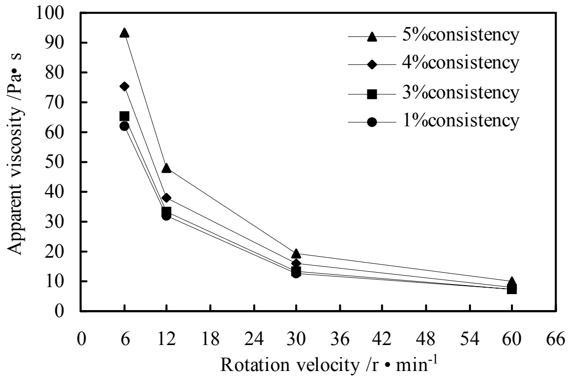

Fig.11 The apparent viscosities of different rotation speed (25°SR beating degree)

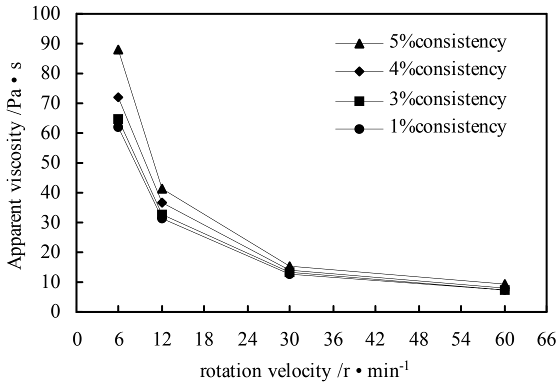

Fig.12 The apparent viscosities of different rotation speed (30°SR beating degree)

When the rheological parameters of non-Newtonian fluid are determined by rotation rheometer, its shearing velocity $\acute{S}$ (s^{-1}) can be calculated by the following equation (Han *et al.* 1993):

$$\acute{S} = B_P \gamma_N \tag{4}$$

Where, γ_N is the same as that of above, and B_P is the modified coefficient (no dimension).

$$B_P = \frac{1-\left(R_1 / R_2\right)^2}{n \cdot [1-(R/R_2)^{2/n}]} \tag{5}$$

As shown in the equation (5), B_P is correlated to R_2, R_1 and n. Assume that the low consistency TMP from Chinese fir thinning wood be the non-Newtonian fluid, there would be such a constitutive equation to describe it as follows:

$$\eta_a = K\acute{S}^{n-1} \tag{6}$$

Where, η_a, $\acute{S}$ are the same as that of above. The value of K refers to the extent of denseness of fluid. The higher the value of K, the denser the fluid is. n describes the extent of departure of Newtonian fluid. Based on experimental data, the rheological models described by constitutive equations are set up, as shown in Table 1. All these constitutive equations are checked by relative coeffi-

cient method, which exhibits that they are markedly correlated at the level of 0.05.

Table 2. Rheological indexes of K and *n* of different consistencies pulp from Chinese fir thinning wood

Beating degree	Rheological indexes	Pulp consistency /%									
		0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
15^0SR	K/ Pa·s ^{n}	173.8	194.2	266.1	348.6	473.0	771.2	—	—	—	—
	n	0.043	0.039	0.031	0.027	0.022	0.015	—	—	—	—
20^0SR	K/ Pa·s ^{n}	160.1	177.2	183.8	197.0	219.4	257.8	302.5	395.4	542.4	841.3
	n	0.046	0.042	0.041	0.039	0.036	0.032	0.029	0.025	0.020	0.014
25^0SR	K/ Pa·s ^{n}	162.1	168.8	174.0	186.6	204.0	217.5	258.8	323.8	465.0	570.8
	n	0.045	0.044	0.043	0.041	0.038	0.036	0.032	0.028	0.022	0.020
30^0SR	K/ Pa·s ^{n}	136.7	152.8	156.8	173.8	180.2	197.4	239.1	286.3	383.0	459.4
	n	0.053	0.048	0.047	0.043	0.042	0.039	0.034	0.030	0.024	0.022

From the Table 2, it is found that all the values of n are smaller than 1, which reveals that all the experimental low consistency TMP from Chinese fir thinning wood could be described as pseudoplastic fluids. Also, it indicates that the values of n increase as the consistency becoming smaller. It may be deduced that the rheological properties intent to be similar to that of Newtonian fluid when the pulp consistency are getting very lower.

Conclusions

The results of rheological properties of low consistency TMP from Chinese fir show that the apparent viscosity of pulp changes with the degree of beating, pulp consistency and shearing velocity. With the increasing of pulp consistency, the apparent viscosity of pulp rises gradually. Beating degree of pulp has an effect on microstructure of pulp. Therefore the apparent viscosity of pulp declines when beating degree of pulp goes up. The apparent viscosity of pulp falls down along with the shearing velocity increasing. Based on the results of this experiment, the rheological models are set up, which shows that the fluid types of the low consistency pulp can be assorted to the pseudoplastics fluid, i.e., non-Newtonian fluid. The properties data of low consistency TMP from Chinese fir thinning wood will be used to model machine-products of pulp molding interactions taking place in the transferring equipment of pulp transferring system of the product line.

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